Maximum And Minimum Dark Matter Detection Cross Sections

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(August, 2000)

Abstract

The range of neutralino-proton cross sections for R-parity preserving super-gravity models with GUT scale unification of the gauge coupling constants is examined. The models considered here are mSUGRA, models with non universal soft breaking and D-brane models. It is found that the current dark matter detectors are sampling significant parts of the SUSY parameter space and future detectors could sample almost the entire space. The special regions of parameter space that may be inaccessible to future detectors are seen to have a squark/gluino spectra beyond 1 TeV, but observable at the LHC.

While the existence of dark matter, which is now believed to make up about 30 % of the matter and energy of the universe, has been known for sometime, the nature of dark matter remains unresolved. Supersymmetric models with R parity invariance automatically posses a dark matter candidate, the lightest supersymmetric particle (LSP). We consider here models based on gravity mediated supergravity (SUGRA), where the LSP is generally the lightest neutralino ($\tilde{\chi}_1^0$). Neutralinos in the halo of the Milky Way might be directly detected by their scattering by terrestrial nuclear targets. Such scattering has a spin independent and a spin dependent part. For heavy nuclear targets the former dominates, and it is possible to extract then (to a good approximation) the neutralino -proton cross section, $\sigma_{\tilde{\chi}_1^0-p}$. Current experiments (DAMA, CDMS, UKMDC) have sensitivity to halo $\tilde{\chi}_1^0$ for

$$\sigma_{\tilde{\chi}_1^0-p} \stackrel{>}{\sim} 1 \times 10^{-6} \, \text{pb} \tag{1}$$

and future detectors (GENIUS, Cryoarray) plan to achieve a sensitivity of

$$\sigma_{\tilde{\chi}_1^0-p} \stackrel{>}{\sim} (10^{-9} - 10^{-10}) \, \text{pb} \tag{2}$$

We consider here two questions: (1) what part of the parameter space is being tested by current detectors, and (2) what is the smallest value of $\sigma_{\tilde{\chi}_1^0-p}$ the theory is predicting (i.e. how sensitive must detectors be to cover the full SUSY parameter space). The answer to these questions depends in part on the SUGRA model one is considering and also on what range of theoretical and input parameter one assumes. In the following, we examine three

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models that have been considered in the literature based on grand unification of the gauge coupling constants at $M_G \cong 2 \times 10^{16}$ GeV: (1) Minimal super gravity GUT (mSUGRA) with universal soft breaking at M_G [1]; (2) Nonuniversal soft breaking models with Higgs and third generation scalar masses at M_G [2], and D-brane models (based on type IIB orientifolds [3]) which allow for nonuniversal gaugino masses and nonuniversal scalar masses at M_G [4].

While each of the above models contain a number of unknown parameters, theories of this type can still make relevant predictions for two reasons: (i) they allow for radiative breaking of $SU(2) \times U(1)$ at the electroweak scale (giving a natural explanation of the Higgs mechanism), and (ii) along with calculating $\sigma_{\tilde{\chi}_1^0-p}$, the theory can calculate the relic density of $\tilde{\chi}_1^0$, i.e $\Omega_{\tilde{\chi}_1^0} = \rho_{\tilde{\chi}_1^0}/\rho_c$ where $\rho_{\tilde{\chi}_1^0}$ is the relic mass density of $\tilde{\chi}_1^0$ and $\rho_c = 3H_0^2/8\pi G_N$ (H_0 is the Hubble constant and G_N is the Newton constant). Both of these greatly restrict the parameter space. In general one has $\Omega_{\tilde{\chi}_1^0} h^2 \sim (\int_0^{x_f} dx \langle \sigma_{\text{ann}} v \rangle)^{-1}$ (where σ_{ann} is the neutralino annihilation cross section in the early universe, v is the relative velocity, $x_f = kT_f/m_{\tilde{\chi}_1^0}$, T_f is the freeze out temperature, $\langle ... \rangle$ means thermal average and $h = H_0/100$ km s^{-1}Mpc^{-1}). The fact that these conditions can be satisfied for reasonable parts of the SUSY parameter space represents a significant success of the SUGRA models.

In the following we will assume $H_0 = (70 \pm 10)$km s^{-1}Mpc^{-1} and matter (m) and baryonic (b) relic densities of $\Omega_m = 0.3 \pm 0.1$ and $\Omega_b = 0.05$. Thus $\Omega_{\tilde{\chi}_1^0} h^2 = 0.12 \pm 0.05$. The calculations given below allow for a 2σ spread, i.e. we take [5]

$$0.02 \leq \Omega_{\tilde{\chi}_1^0} h^2 \leq 0.25. \tag{3}$$

It is clear that when the MAP and Planck sattelites determine the cosmological parameters accurately, the SUGRA dark matter predictions will be greatly sharpened.

I. CALCULATIONAL DETAILS

In order to get reasonably accurate results, it is necessary to include a number of theoretical corrections in the analysis. We list here the main ones used in the calculations below: (i) In relating the theory at M_G to phenomena at the electroweak scale, the two loop gauge and one loop Yukawa renormalization group equations (RGE) are used, iterating to get a consistent SUSY spectrum. (ii) QCD RGE corrections are further included below the SUSY breaking scale for contributions involving light quarks. (iii) A careful analysis of the light Higgs mass m_h is necessary (including two loop and pole mass corrections) as the current LEP limits impact sensitively on the relic density analysis for $\tan\beta \leq 5$. (iv) L-R mixing terms are included in the sfermion (mass)^2 matrices since they produce important effects for large $\tan\beta$ in the third generation. (v) One loop corrections are included to m_b and m_τ which are again important for large $\tan\beta$. (vi) The experimental bounds on the $b \to s\gamma$ decay put significant constraints on the SUSY parameter space and theoretical calculations here include the leading order (LO) and approximate NLO corrections. We have not in the following imposed $b-\tau$ (or $t-b-\tau$) Yukawa unification or proton decay constraints as these depend sensitively on unknown post-GUT physics. For example, such constraints do not naturally occur in the string models where $SU(5)$ (or $SO(10)$) gauge symmetry is broken by Wilson lines at M_G (even though grand unification of the gauge coupling constants at M_G for such string models is still required).

All the above corrections are under theoretical control except for the $b \to s\gamma$ analysis where a full NLO calculations has not been done. (We expect that while the full analysis might modify the regions of parameter space excluded by the $b \to s\gamma$ experimental constraint, the minimum and maximum values of $\sigma_{\tilde{\chi}_1^0-p}$ would probably not be significantly changed.) The analysis of $\sigma_{\tilde{\chi}_1^0-p}$, taking into account the above theoretical corrections has now been carried out by several groups obtaing results in general agreement [6–12]. These results are presented below.

Accelerator bounds significantly limit the SUSY parameter space. In the following we assume the LEP bounds [10] $m_h > 104(100)$ GeV for $\tan\beta$=3(5) and $m_{\chi_1^\pm} > 104(100)$ GeV. (For $\tan\beta > 5$, the m_h bounds do not produce a significant constraint [13].) For $b \to s\gamma$ we assume an allowed range of 2σ from the CLEO data [14]:

$$1.8 \times 10^{-4} \leq B(B \to X_s\gamma) \leq 4.5 \times 10^{-4} \tag{4}$$

The Tevatron gives a bound of $m_{\tilde{g}} \geq 270$ GeV(for $m_{\tilde{q}} \cong m_{\tilde{g}}$) [15].

Theory allows one to calculate the $\tilde{\chi}_1^0$-quark cross section and we follow the analysis of [16] to convert this to $\tilde{\chi}_1^0 - p$ scattering. For this one needs the $\pi - N \ \sigma$ term,

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle p|\bar{u}u + \bar{d}d|p\rangle, \tag{5}$$

$\sigma_0 = \sigma_{\pi N} - (m_u + m_d)\langle p|\bar{s}s|p\rangle$ and the quark mass ratio $r = m_s/(1/2)(m_u + m_d)$. We use here $\sigma_{\pi N} = 65$MeV, from recent analyses [17,18] based on new $\pi - N$ scattering data, $\sigma_0 = 30$ MeV [19] and r= 24.4 ± 1.5 [20]. Older $\pi - N$ data gave $\sigma_{\pi N} \cong 45$ GeV [21], which if used would reduce the overall $\sigma_{\tilde{\chi}_1^0-p}$ by a factor of about 3.

II. MSUGRA MODEL

We consider first the mSUGRA model where the most complete analysis has been done. mSUGRA depends on four parameters and one sign: m_0 (universal scalar mass at M_G), $m_{1/2}$ (universal gaugino mass at M_G), A_0 (universal cubic soft breaking mass, $\tan\beta = \langle H_2\rangle/\langle H_1\rangle$ (where $\langle H_{2,1}\rangle$ gives rise to (up, down) quark masses) and $\mu/|\mu|$(where μ is the Higgs mixing parameter in the superpotential, $W_\mu = \mu H_1 H_2$). One conventionally restricts the range of these parameters by "naturalness" conditions and in the following we assume $m_0 \leq 1$ TeV, $m_{1/2} \leq 600$ GeV (corresponding to $m_{\tilde{g}} \leq 1.5$ TeV, $m_{\tilde{\chi}_1^0} \leq 240$ GeV), $|A_0/m_0| \leq 5$, and $2\leq \tan\beta \leq 50$. Large $\tan\beta$ is of interest since SO(10) models imply $\tan\beta \geq 40$ and also $\sigma_{\tilde{\chi}_1^0-p}$ increases with $\tan\beta$. $\sigma_{\tilde{\chi}_1^0-p}$ decreases with $m_{1/2}$ for large $m_{1/2}$, and thus if one were to increase the bound on $m_{1/2}$ to 1 TeV ($m_{\tilde{g}} \leq 2.5$ TeV), the cross section would drop by a factor of 2-3.

The maximum $\sigma_{\tilde{\chi}_1^0-p}$ arise then for large $\tan\beta$ and small $m_{1/2}$. This can be seen in Fig.1 where $(\sigma_{\tilde{\chi}_1^0-p})_{\max}$ is plotted vs. $m_{\tilde{\chi}_1^0}$ for $\tan\beta$=20, 30, 40 and 50. Fig. 2 shows $\Omega_{\tilde{\chi}_1^0}h^2$ for $\tan\beta = 30$ when the cross section takes on its maximum value. Current detectors obeying Eq (1) are then sampling the parameter space for large $\tan\beta$, small $m_{\tilde{\chi}_1^0}$ and small $\Omega_{\tilde{\chi}_1^0}h^2$ i.e

$$\tan\beta \gtrsim 25, \ m_{\tilde{\chi}_1^0} \lesssim 90\text{GeV}, \ \Omega_{\tilde{\chi}_1^0}h^2 \lesssim 0.1 \tag{6}$$

To discuss the minimum cross section, it is convenient to consider first $m_{\tilde{\chi}_1^0} \overset{<}{\sim} 150$ GeV ($m_{1/2} \leq 350$) where no coannihilation occurs. The minimum cross section occurs for small $\tan\beta$. From Fig.3 one sees

$$\sigma_{\tilde{\chi}_1^0 - p} \overset{>}{\sim} 4 \times 10^{-9}\text{pb}; \; m_{\tilde{\chi}_1^0} \overset{<}{\sim} 140\text{GeV} \tag{7}$$

which would be accessible to detectors that are currently being planned (e.g. GENIUS).

For larger $m_{\tilde{\chi}_1^0}$, i.e. $m_{1/2} \overset{>}{\sim} 150$ the phenomena of coannihilation can occur in the relic density analysis since the light stau, $\tilde{\tau}_1$, (and also $\tilde{e}_R$, $\tilde{\mu}_R$) can become degenerate with the $\tilde{\chi}_1^0$. The relic density constraint can then be satisfied in narrow corridor of m_0 of width $\Delta m_0 \overset{<}{\sim} 25$ GeV, the value of m_0 increasing as $m_{1/2}$ increases [8]. Since m_0 and $m_{1/2}$ increase as one progresses up the corridor, $\sigma_{\tilde{\chi}_1^0 - p}$ will generally decrease.

We consider first the case $\mu > 0$ [22]. One finds in general that $\sigma_{\tilde{\chi}_1^0 - p}$ also decreases as A_0 increases. Fig.4 shows $\sigma_{\tilde{\chi}_1^0 - p}$ in the domain of large A_0 and for two values of $\tan\beta$. One sees that the smaller $\tan\beta$ still gives the lower cross section, though the difference is mostly neutralized at larger $m_{1/2}$. (For large $\tan\beta$, m_0 also becomes large to satisfy the relic density constraint i.e $m_0 \cong 700$ GeV for $\tan\beta$=40, $m_{1/2} = 600$ GeV.) We have in general for this regime

$$\sigma_{\tilde{\chi}_1^0 - p} \overset{>}{\sim} 1 \times 10^{-9}\text{pb}; \; \text{for} \, m_{1/2} \leq 600\text{GeV}, \mu > 0, \, A_0 \leq 4m_{1/2}. \tag{8}$$

This is still within the sensitivity range of proposed detectors.

When μ is negative an "accidental" cancellation can occur in part of the parameter space in the coannihilation region which can greatly reduce $\sigma_{\tilde{\chi}_1^0 - p}$ [9]. This can be seen in Fig.5, where starting with small $\tan\beta$ the cross section decreases, leading to a minimum at about $\tan\beta$=10, and then increases again for larger $\tan\beta$. At the minimum one has $\sigma_{\tilde{\chi}_1^0 - p} \cong 1 \times 10^{-12}$ for $\tan\beta$=10 and $m_{1/2} = 600$ GeV. More generally one has

$$\sigma_{\tilde{\chi}_1^0 - p} < 1 \times 10^{-10}\text{pb} \tag{9}$$

for the parameter domain when $4 \overset{<}{\sim} \tan\beta \overset{<}{\sim} 20$, $m_{1/2} \overset{>}{\sim} 450\text{GeV}(m_{\tilde{g}} \overset{>}{\sim} 1.1\text{TeV})$, $\mu < 0$. In this domain, $\sigma_{\tilde{\chi}_1^0 - p}$ would not be accessible to any of the currently planned detectors. However, mSUGRA also then predicts that this could happen only when the gluino and squarks have masses greater than 1 TeV (and for only a restricted region of $\tan\beta$) a result that could be verified at the LHC.

III. NONUNIVERSAL SUGRA MODELS

In the discussion of SUGRA models with nonuniversal soft breaking, universality for the first two generations of squark and slepton masses at M_G is usually maintained to suppress flavor changing neutral currents. One allows, however, the Higgs and third generation squark and slepton masses to become nonuniversal. The masses may then be parametrized at M_G as follows:

$$
\begin{aligned}
m_{H_1}^2 &= m_0^2(1 + \delta_1); \quad m_{H_2}^2 = m_0^2(1 + \delta_2); \\
m_{q_L}^2 &= m_0^2(1 + \delta_3); \quad m_{t_R}^2 = m_0^2(1 + \delta_4); \quad m_{\tau_R}^2 = m_0^2(1 + \delta_5); \\
m_{b_R}^2 &= m_0^2(1 + \delta_6); \quad m_{l_L}^2 = m_0^2(1 + \delta_7).
\end{aligned} \tag{10}
$$

4

where $q_L \equiv (t_L, b_L)$, $l_L \equiv (\nu_\tau, \tau_L)$. Here m_0 is the universal mass of the first two generations and δ_i are the Higgs and third generation deviations from universality. In the following we will restrict the δ_i to obey

$$-1 \leq \delta_i \leq 1. \tag{11}$$

The lower limit on δ_i is necessary to prevent tachyonic behavior, and the condition $\delta_i \leq 1$ is taken as a reasonable upper bound. We also maintain gauge and gaugino mass unification at M_G.

While these models contain a large number of new parameters, their effects on $\sigma_{\tilde{\chi}_1^0 - p}$ can be charcterized approximately by the signs of $\delta_1...\delta_4$ [11]. Thus the choice of δ_3, δ_4, $\delta_1 < 0$ and $\delta_2 > 0$ can greatly increase $\sigma_{\tilde{\chi}_1^0 - p}$, and the reverse choice can reduce $\sigma_{\tilde{\chi}_1^0 - p}$ (though by a much lesser amount). The possible increase is shown in Fig.6 for $\tan\beta = 7$, $\mu > 0$ where nonuniversal soft breaking increases $\sigma_{\tilde{\chi}_1^0 - p}$ by a factor of 10-100 compared to the universal case. Thus it is possible for detectors to probe regions of smaller $\tan\beta$ with nonuniversal breaking, and detectors obeying Eq. (1) can probe part of the parameter space for $\tan\beta$ as low as $\tan\beta \simeq 4$.

The minimum cross section occurs (as in mSUGRA) at the lowest $\tan\beta$ and at the largest $m_{1/2}$ i.e. in the coannihilation region. We limit ourselves here to the case where only the Higgs masses are nonuniversal i.e. $\delta_{1,2} \neq 0$. One finds then results similar to mSUGRA i.e. $\sigma_{\tilde{\chi}_1^0 - p} \gtrsim 10^{-9}$ pb for $\mu > 0$, $m_{1/2} \leq 600$ GeV. For $\mu < 0$, there can again be a cancellation of matrix elements reducing the cross section to 10^{-12} pb when $m_{1/2} = 600$ GeV in a restricted part of the parameter space when $\tan\beta \simeq 10$ [23].

IV. D-BRANE MODELS

Recent advances in string theory have stimulated again the construction of string inspired phenomenologically viable models. One type, based on type IIB orientifolds [3] puts the Standard Model on sets of 5 branes. These models are of interest in that they can lead to a pattern of soft breaking different from what can naturally arise in conventional supergravity GUTs. An interesting example [4] has the following soft breaking pattern at M_G:

$$\tilde{m}_1 = \tilde{m}_3 = -A_0 = \sqrt{3}cos\theta_b\Theta_1 e^{-i\alpha_1}m_{3/2} \tag{12}$$
$$\tilde{m}_2 = \sqrt{3}cos\theta_b(1 - \Theta_1^2)^{1/2}m_{3/2}$$

where and $\tilde{m}_i$ are the gaugino masses, and

$$m_{12}^2 = (1 - 3/2sin^2\theta_b)m_{3/2}^2 \text{ for } q_L,\, l_L,\, H_1,\, H_2 \tag{13}$$
$$m_1^2 = (1 - 3sin^2\theta_b)m_{3/2}^2 \text{ for } u_R,\, d_R,\, e_R.$$

Thus the $SU(2)$ doublets are all degenerate at M_G but different from the singlets. We note Eq. (13) implies $\theta_b <$0.615.

We consider first the case with no CP violating phases in the soft breaking sector, i.e. α_1=0 and the μ parameter real. In general $\sigma_{\tilde{\chi}_1^0 - p}$ is a decreasing function of θ_b since the squark and slepton masses increase as θ_b decreases. This is illustrated in Fig. 7 where $\sigma_{\tilde{\chi}_1^0 - p}$

is plotted for $\tan\beta=10$, $m_{3/2} = 175$ GeV with $\theta_b = 0.5$ (upper curve) and $\theta_b = 0.2$ (lower curve). One has that current detectors obeying Eq. (1) are sensitive to the model in the domain when $\tan\beta \gtrsim 15$. However $m_{\tilde{\chi}_1^0}$ is quite small when $\tan\beta$ is close to the minimum value.

The lower bound on $\sigma_{\tilde{\chi}_1^0-p}$ should occur when θ_b and $\tan\beta$ are small. Fig. 8 shows the minimum cross section for $m_{\tilde{\chi}_1^0} \leq 300$ GeV, $\mu > 0$. One sees $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-9}$ pb. As in mSUGRA, a cancellation of matrix elements can occur for $\mu < 0$, allowing a smaller cross section in the domain $7 \lesssim \tan\beta \lesssim 30$ and reaching a minimum of $\simeq 10^{-12}$ pb for $m_{3/2} = 600$ GeV at $\tan\beta \simeq 12$. These low cross sections again imply very heavy gluinos i.e $m_{\tilde{g}} \gtrsim 950$ GeV. The D-brane model also possesses an interesting new region of coannihilation for $\Theta_1 \simeq 0.8$ when the light chargino $\tilde{\chi}_1^{\pm}$ can become degenerate with $\tilde{\chi}_1^0$, which has not been analyzed here.

CP violating phases produce contributions to the electric dipole moments of the electron d_e, and neutron d_n. The bound on d_e is $d_e < 4.3 \times 10^{-27}$ ecm at 95 % C.L. [24], and one must constrain the parameter space to satisfy this. This generally reduces $\sigma_{\tilde{\chi}_1^0-p}$ by a factor of 2-3 [12]. However models with CP violating phases require a great deal of fine tuning unless $\tan\beta \leq 3$-5, so one would expect in this case $\sigma_{\tilde{\chi}_1^0-p}$ to be quite small.

V. SUMMARY

We have examined here the neutralino-proton cross section for a number of SUGRA type models. In all the models considered, there are regions of parameter space with $\tilde{\chi}_1^0 - p$ cross sections of the size that could be observed with current detectors. Thus with the sensitivity of Eq. (1), detectors would be sampling regions of the parameter space for mSUGRA where $\tan\beta \gtrsim 25$, $m_{\tilde{\chi}_1^0} \lesssim 90$GeV and $\Omega_{\tilde{\chi}_1^0}h^2 \lesssim 0.1$. Nonuniversal models can have larger cross sections and so detectors could sample down to $\tan\beta \gtrsim 4$, while for the D-brane models considered, detectors could sample down to $\tan\beta \gtrsim 15$.

The minimum cross sections these models predict are considerably below current sensitivity. Thus for mSUGRA one finds for $\mu > 0$

$$\sigma_{\tilde{\chi}_1^0-p} \gtrsim 1 \times 10^{-9}\text{pb for } m_{1/2} \leq 600\text{GeV}, \mu > 0. \tag{14}$$

where $m_{1/2} = 600$ GeV corresponds to $m_{\tilde{g}} \cong 1.5$ TeV, $m_{\tilde{\chi}_1^0} \cong 240$ TeV. This is still in the range that would be accessible to detectors being planned (such as GENIUS or Cryoarray). For $\mu < 0$, a cancellation can occur in certain regions of parameter space allowing the cross sections to fall below Eq. (14), Thus

$$\sigma_{\tilde{\chi}_1^0-p} < 1 \times 10^{-10}\text{pb for } 4 \lesssim \tan\beta \lesssim 20, \mu < 0, m_{1/2} \gtrsim 450\text{GeV} \tag{15}$$

and reaching a minimum of $\sigma_{\tilde{\chi}_1^0-p} \cong 1 \times 10^{-12}$ pb for $\tan\beta=10$, $m_{1/2}=600$ GeV, $\mu < 0$. This domain would appear not to be accessible to future planned detectors. Since $m_{1/2}=450$ GeV corresponds to $m_{\tilde{g}} \cong 1.1$ TeV, this region of parameter space would imply a gluino squark spectrum at the LHC above 1 TeV.

The above results holds for the mSUGRA model. While a full analysis of coannihilation has not been carried out for the nonuniversal and D-brane models, results similar to the above

hold for these over large regions of parameter space. Thus for nonuniversal Higgs masses and for the D-brane model one finds $\sigma_{\tilde{\chi}_1^0-p} \gtrsim 10^{-9}$ pb for $\mu > 0$, while a cancellelation allows $\sigma_{\tilde{\chi}_1^0-p}$ to fall to 10^{-12} pb for $\mu < 0$ at $\tan\beta \simeq 10$ (with again a gluino/squark mass spectrum in the TeV domain).

In the above we have limited $m_{1/2}$ to $m_{1/2} \leq 600$ GeV ($m_{\tilde{g}} \leq 1.5$ TeV). Increasing $m_{1/2}$ lowers the cross section. Thus allowing $m_{1/2} = 1$ TeV ($m_{\tilde{g}} \cong 2.5$ TeV) would reduce the minimum cross section by a factor of about 2-3. Also using the earlier value of $\sigma_{\pi N} = 45$ MeV [21] rather than the most recent value $\sigma_{\pi N} = 65$ MeV [17,18] would reduce $\sigma_{\tilde{\chi}_1^0-p}$ by a factor of 3.

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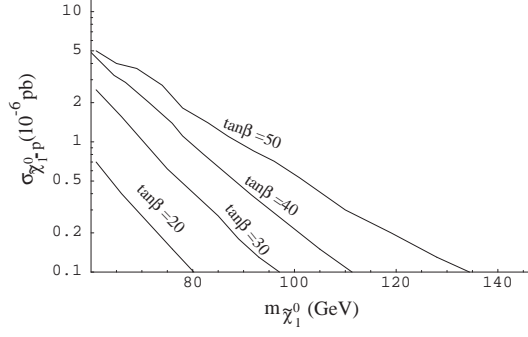[25] R. Arnowitt, B. Dutta and Y. Santoso, Coannihilation in SUGRA and D-brane models, in preparation.

FIG. 1. $(\sigma_{\tilde{\chi}_1^0-p})_{\max}$ for mSUGRA obtained by varying A_0 over the parameter space for $\tan\beta = 20$, 30, 40, and 50[11]. The relic density constraint, Eq.(3) has been imposed.
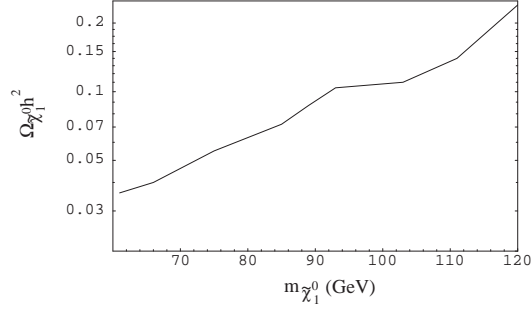

FIG. 2. $\Omega_{\tilde{\chi}_1^0}h^2$ for mSUGRA when $(\sigma_{\tilde{\chi}_1^0-p})$ takes on its maximum value for $\tan\beta = 30$ [11].
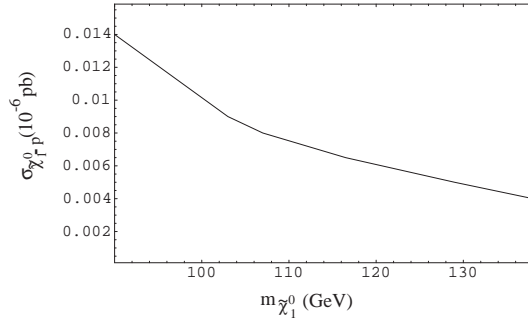

FIG. 3. $(\sigma_{\tilde{\chi}_1^0-p})_{\min}$ for $m_{\tilde{\chi}_1^0} \leq 140$ GeV for mSUGRA obtained by varying A_0 for $\tan\beta = 3$ with the relic density constraint, Eq.(3)[25].
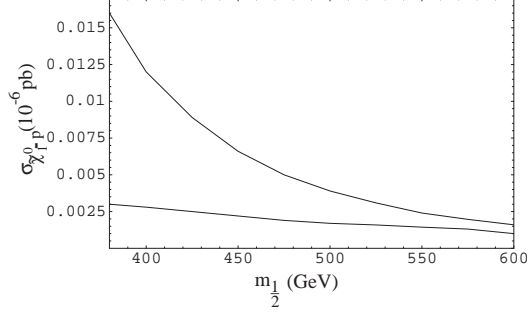
FIG. 4. $(\sigma_{\tilde{\chi}_1^0-p})$ for mSUGRA in the coannihilation region for $\tan\beta = 40$ (upper curve) and $\tan\beta = 3$ (lower curve), $A_0 = 4m_{1/2}$, $\mu > 0$[25].
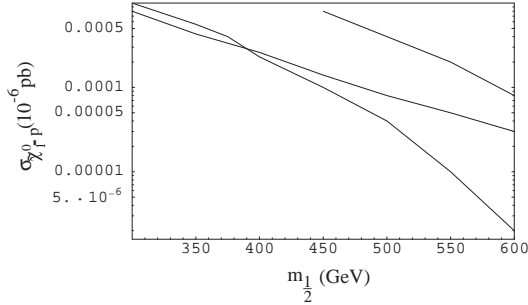

FIG. 5. $(\sigma_{\tilde{\chi}_1^0-p})$ for mSUGRA and $\mu < 0$ for (from top to bottom on right) $\tan\beta$=20, 5 and 10. Note that for $\tan\beta \geq 10$, the curves terminate at the left due to the $b \rightarrow s\gamma$ constraint[25].
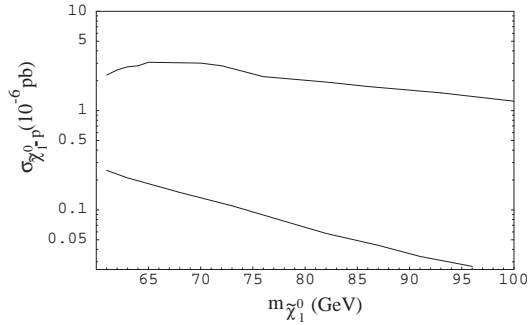

FIG. 6. Universal mSUGRA (lower curve) and nonuniversal soft breaking (upper curve) for $\tan\beta = 7$, $\mu > 0$. The nonuniversal curve has δ_3, δ_2, $\delta_1 < 0$ $\delta_2 > 0$[11].
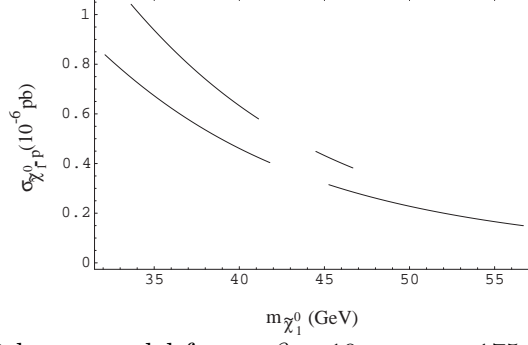
FIG. 7. $\sigma_{\tilde{\chi}_1^0-p}$ for the D-brane model for $\tan\beta = 10$, $m_{3/2} = 175$ GeV, $\mu > 0$. Upper curve is θ_b=0.5, lower curve θ_b=0.2[12].
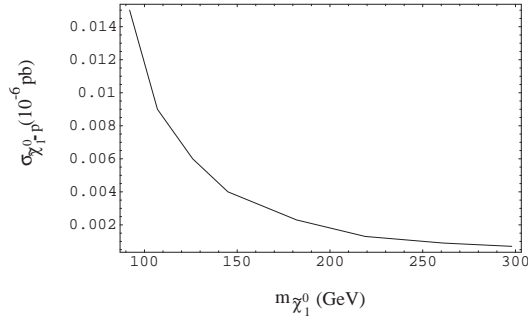

FIG. 8.   Minimum $\sigma_{\tilde{\chi}_1^0-p}$ for the D-brane model for $m_{3/2} = 600$ GeV, $\mu > 0$[25].